TRACKING GALILEO AT EARTH-2 PERIGEE USING THE TRACKING AND DATA RELAY SATELLITE SYSTEM

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The Tracking and Data Relay Satellite System (TDRSS) was successfully used to track the Galileo spacecraft on December 8, 1992, during the Galileo Earth-2 flyby. This flyby enabled Galileo to obtain a gravity-assisted energy increase as part of the Venus-Earth-Earth trajectory en route to the planet Jupiter. Due to the low perigee altitude of about 300 km, there was a gap in DSN coverage for nearly two hours around perigee, from 13:49-15:40 GMT. During this time, Galileo was within the field-of-view (FOV) of the spare Tracking and Data Relay Satellite (TDRS) at 62 deg W longitude. In order to obtain a continuous Doppler arc throughout the perigee period, the TDRS was configured to observe the Galileo 2.3-GHz carrier signal with one of its S-band Single-Access (SA) antennas, and coherently relay the signal to the White Sands Ground Terminal (WSGT), where a special baseband tracking receiver was installed to enable reliable carrier phase (Doppler) extraction during the high signal dynamics at perigee. An S-band calibration signal transmitted from WSGT was simultaneously observed with the other TDRS SA antenna in order verify system performance in real time and to remove the effects of TDRS motion during the tracking, To our knowledge, this represents the first time the TDRS System has been used to track a spacecraft on a hyperbolic trajectory. We will describe the techniques used to acquire these data, and examine the perigee Doppler data in the context of the fully reconstructed flyby trajectory.

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INTRODUCTION

The Galileo spacecraft is in the midst of a 6-year interplanetary cruise en route to the planet Jupiter, where it will arrive in December, 1995. To achieve the required energy for reaching Jupiter, the cruise incorporates one Venus gravity assist and two Earth gravity assists. The first Earth gravity assist (EGA1) was on December 8, 1990, 20:34:34 UTC at a perigee altitude of about 960 km. Nearly continuous two-way Doppler and range data were collected from the Deep Space Network (DSN) from November 2 to December 13. However, there was a gap of about 1 hr 9 min around perigee, where no two-way data were collected.

Subsequent analysis of the fly-by trajectory [1] indicated an anomalous apparent velocity increase of 4 mm/s during this gap in two-way tracking coverage near perigee, That is, in order to obtain a good fit between the inbound and outbound Galileo trajectories, it was necessary to include an impulsive maneuver of about 4 mm/s along the Galileo velocity vector at perigee. While this small velocity anomaly had no significant impact on mission navigation, and did not influence the successful Earth-1 gravity assist, there was considerable interest in the project navigation and radio science teams in understanding its origin. A variety of possible sources for the velocity anomaly have been investigated, including mismodeling of maneuvers on the spacecraft, uncalibrated Earth propagation media effects, errors in the orbit determination software, unreported thruster firings, or even new physical phenomena. To date, however, no suitable explanation for the anomaly has been found, As a result of this experience, an effort was made to provide continuous tracking of Galileo throughout its Earth-2 encounter perigee.

TRACKING FOR THE EARTH-2 FLYBY

The second Earth flyby occurred on December& 1992, 15:09 UTC, at a 303-km altitude over the South Atlantic. The low perigee altitude led to a gap of nearly two hours in visibility from the DSN, with a resulting gap in two-way Doppler tracking, To partially fill this visibility gap, one-way Doppler tracking was scheduled at ground stations at Santiago, Perth, and Okinawa, providing tracking coverage for all but about 25 minutes around perigee.

To fill this remaining gap in tracking coverage at perigee, an investigation was made of the possibility of using one of the geostationary satellites in the Tracking and Data Relay Satellite System (TDRSS). At the time of the Earth-2 flyby, there were four TDRSS satellites on orbit, at longitudes of 41 deg W longitude, 62 deg W longitude, 171 deg W longitude, and 174 deg W longitude. It was found that the Tracking and Data Relay Satellite (TDRS) at 62 deg W longitude, which we will refer to as TDRS-62W, provided the best visibility of the Galileo perigee trajectory. Figure 1 shows a visibility timeline for the ground stations and for the TDRSS. Figure 2 shows the Galileo perigee trajectory as viewed from TDRS-62W. Indicated on the figure is the elliptical field-of-view (FOV) constraints for the TDRS-62W SA antennas.

GALILEO DATA ACQUISITION USING THE TDRSS

Due to the PCM/PSK/PM modulation scheme used by JPL deep space missions, as well as the high signal dynamics expected at perigee, there was considerable uncertainty as to whether the nominal TDRSS tracking receiver at the White Sands Ground Terminal (WSGT) could successfully lock onto and track the Galileo carrier through perigee. Instead, it was decided to use a new digital baseband receiver developed at JPL to perform the carrier acquisition and tracking. This receiver, which we refer to as the Experimental

Tone Tracker (E'fT), is derived from the Turbo-Rogue GPS tracking receiver [2] and features two IF signal inputs and up to 24 separate tone models which can be simultaneously tracked,

Figure 3 shows the configuration used to perform the Galileo tracking. One SA antenna of the TDRS-62W received the 2.3-GHz (S-band) signal transmitted from the Galileo low-gain antenna. The TDRS receives a 15.15-GHz pilot tone from WSGT which serves as a frequency reference for the TDRS spacecraft, Based on this uplink frequency reference, the TDRS-62W generates a mixing LO to coherently translate the Galileo signal to a frequency of 13.7 GHz for transmission to WSGT. Figure 4 details the frequency scheme on board the TDRS-62W for these observations,

At WSGT, the received 13.7-GHz signal is downconverted to a 370-MHz IF frequency, which is subsequently processed by the WSGT tracking receiver. This mixing process is typically predicts-driven to remove the *a priori* expected Doppler shift from the signal. For our purposes, it was decided to have a simple fixed-frequency downconversion and handle the signal dynamics in the baseband tracking processor. we defeated the WSGT Doppler compensation by supplying a fixed-frequency mixing LO to the S-band Single-Access (SSA) downconverter. We adjusted the frequency of this mixing LO to provide a 350-MHz IF frequency, based on the signal requirements of the ETT.

Simultaneous to the Galileo tracking, an S-band coherent beacon signal was transmitted at WSGT and received in the other SA antenna of TDRS-62W, where it was also frequency translated and re-transmitted back to WSGT. This signal was downconverted in a similar way and tracked in the other IF channel of the ETT. There were two motivations for including this calibration beacon signal. First, it provided a valuable real-time check of the end-to-end performance of the TDRSS system, including our modifications to the downconverters and our ETT processor. Secondly, the measured phase of the beacon signal provides an accurate calibration of any delay changes in the link between TDRS-62W and WSGT. Since the TDRS space-to-ground link is at 13.7 GHz, any delay changes along the TDRS-WSGT link induce phase changes with an effective frequency of twice this, or nearly 30 GHz. Thus tropospheric fluctuations and/or unmodeled spacecraft motion along the TDRS-WSGT line-of-sight can lead to significant corruption of the relayed Galileo Doppler signal. (Unmodeled TDRS motion along the Galileo-TDRS line-of-sight, on the other hand, enters only at the much lower frequency of 2.3 GHz.) The observation scheme used for this Galileo tracking experiment is very similar to the configuration used to support a demonstration of Orbiting Very Long Baseline Interferometry (OVLBI) using the TDRSS in 1986 [3], except the SA antenna points at Galileo rather than an extragalactic radio source. In fact, it was based on this OVLBI experience that the Galileo tracking experiment was proposed.

RESULTS

Figures 5 and 6 show the actual received power and frequency of the Galileo signal during the perigee period. Roughly the first two hours of tracking overlap with the two-way Doppler arc at Canberra, During this period, the Galileo carrier was phase-locked to an uplink signal received from the Canberra DSN site, We acquired this signal at 12:00 GMT and tracked it continuously until 13:45 GMT when, just prior to setting below the Canberra horizon, Galileo switched to a one-way non-coherent downlink signal, phase-locked to the on-board ultra-stable oscillator. At 13:46 GMT we acquired this one-way signal and successfully tracked it through perigee and out to the TDRS-62W FOV limit, which was reached at 15:37 GMT.

We are currently in the process of analyzing this data set, We will describe the processing steps required to correct for TDRS-62W motion based on tracking of the TDRS using the Bilateration Ranging Transponder System (BRTS), and discuss the calibration of the TDRS-WSGT space-to-ground link using the WSGT S-band beacon signal. After calibration, the TDRS-62W Galileo data will be combined with the two-way DSN Doppler data and the one-way data from the other ground tracking sites,

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[1] Kallemeyn, P., "Observations from Galileo Earth-1 flyby reconstruction efforts," GLL-NAV-91-62, Jet Propulsion Laboratory, (Internal Document), April 3, 1991.

[2] Thomas, J. B., "Functional Description of Signal Processing in the Rogue GPS Receiver," JPL Publication 88-15, Jet Propulsion Laboratory, 1988.

[3] Levy, G. S., *et al.,* "Very Long Baseline Interferometric Observations Made with an Orbiting Radio Telescope," Science, 234, 187-189, 1986.

FIGURE CAPTIONS

1. Visibility of Galileo at ground tracking sites and from TDRSS.

2, View of the Galileo trajectory from the TDRS at 62 deg W longitude, showing Galileo attitude and TDRS field-of-view constraint.

3. Experiment configuration for tracking Galileo using the TDRS-62W satellite.

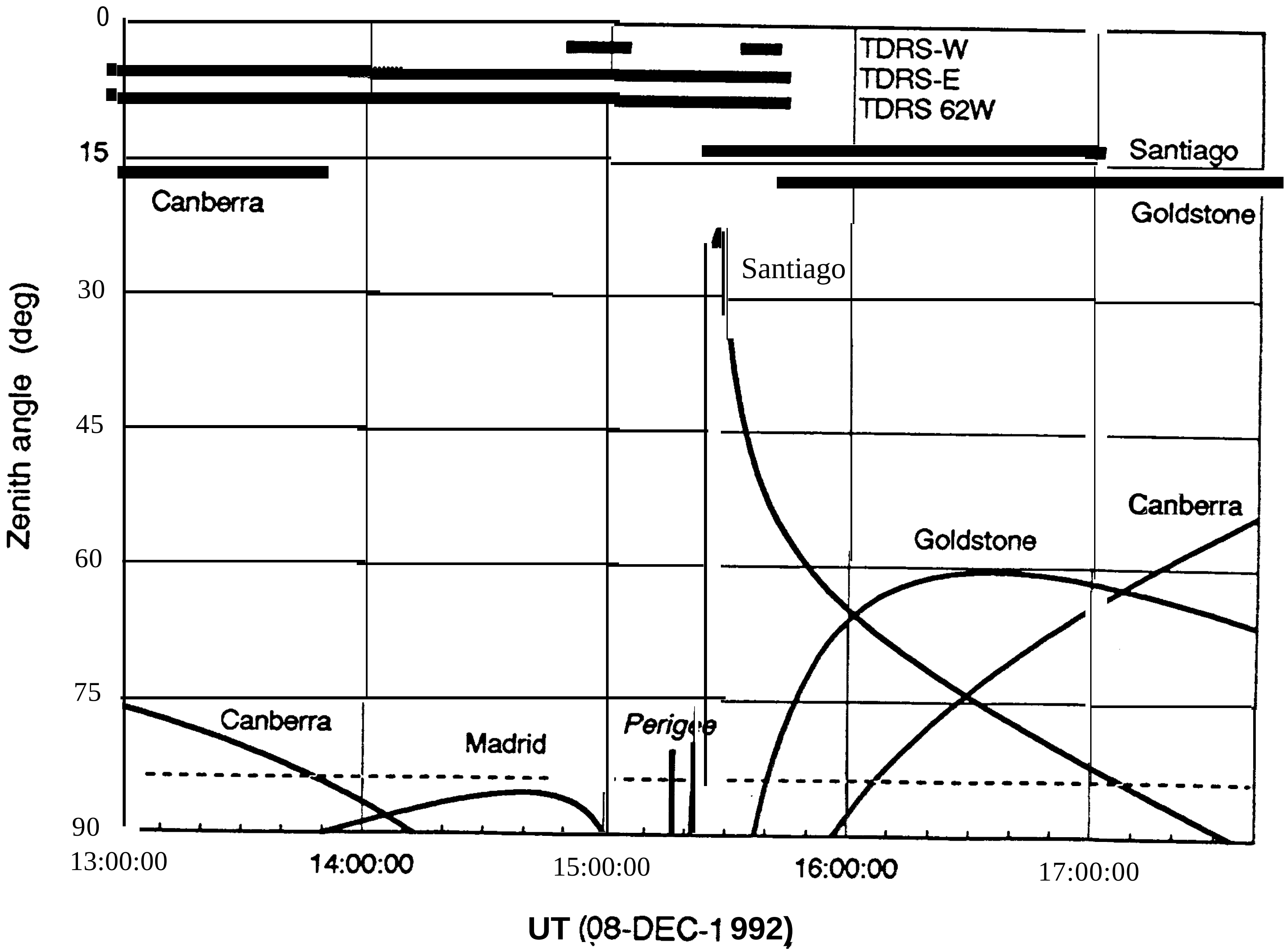
4. Frequency scheme on board TDRS. A 15.15-GHz uplink pilot tone is used to coherently translate the 2.3-GHz S-band signal received at each SA antenna to 13.7 GHz for relay to WSGT.

5. Received carrier power-to-noise-density (C/No) for Galileo carrier signal as relayed through TDRS-62W and tracked at WSGT.

6. Received frequency for Galileo carrier signal as relayed through TDRS-62W and tracked at WSGT.

Figure

Visibility of Galileo During Earth-2 Flyby, 08-DEC-1992



Galileo Earth-2 Flyby 8 Dec 1992

View from TDRS (62 W)

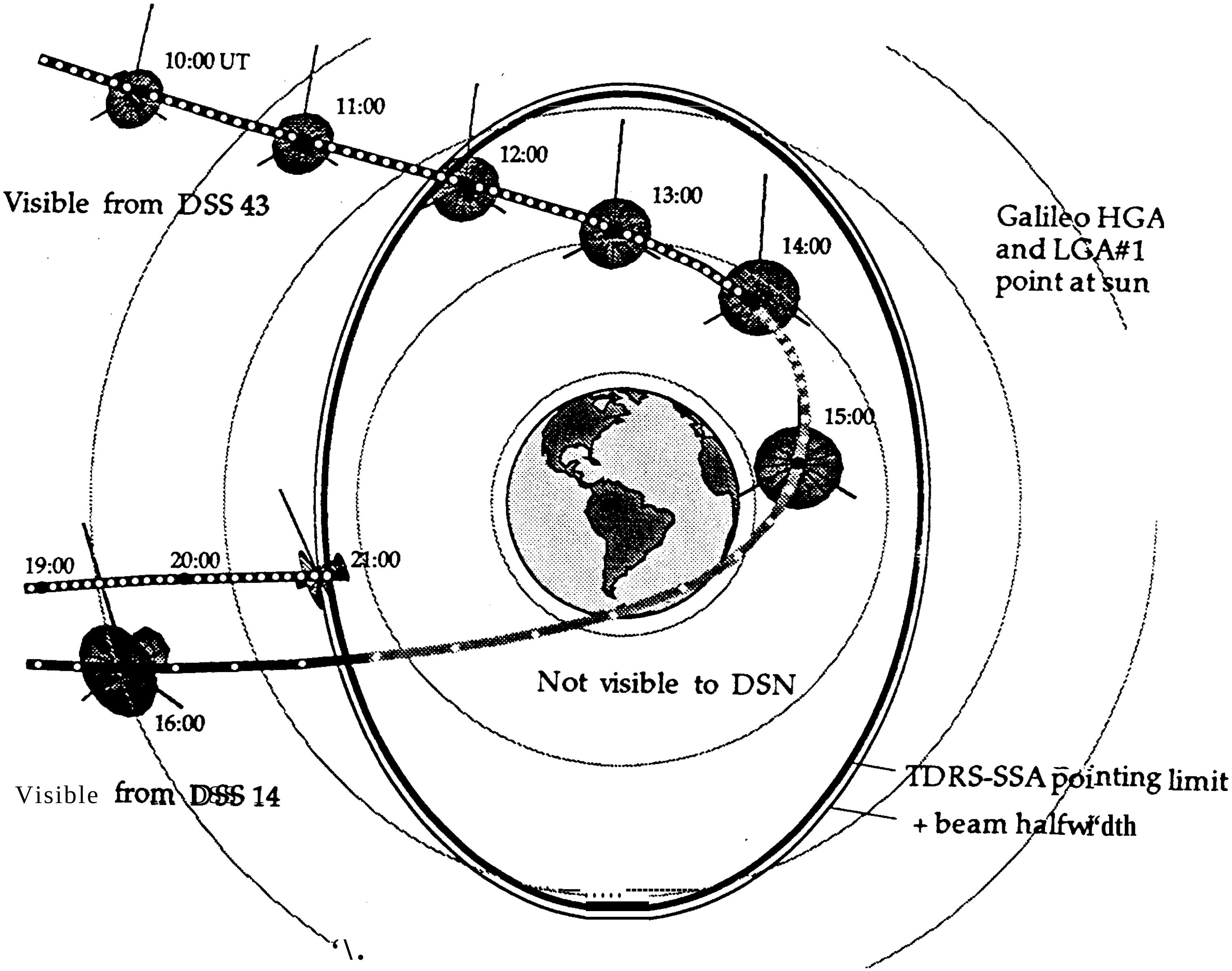


Figure 2

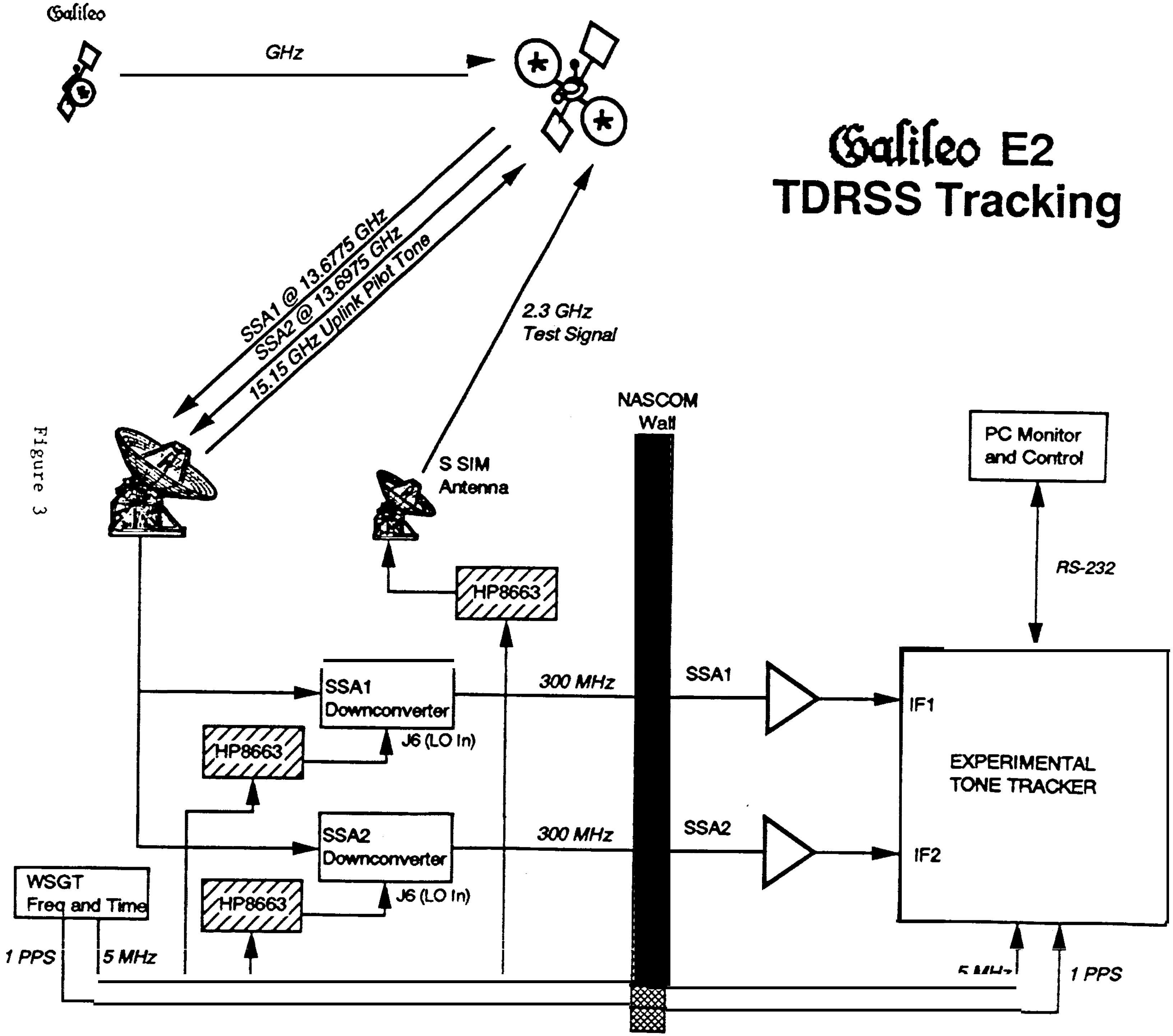


Figure 3

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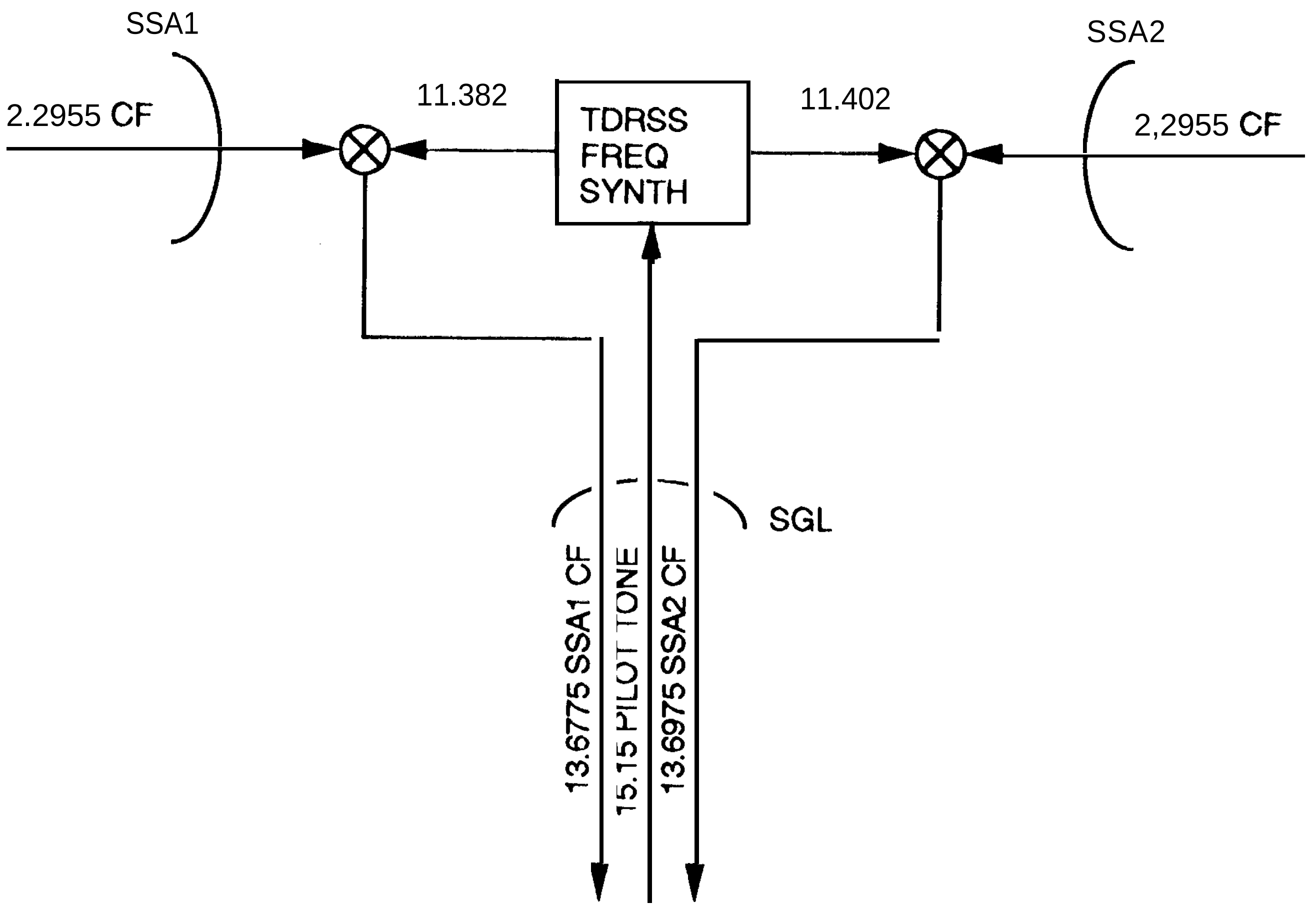
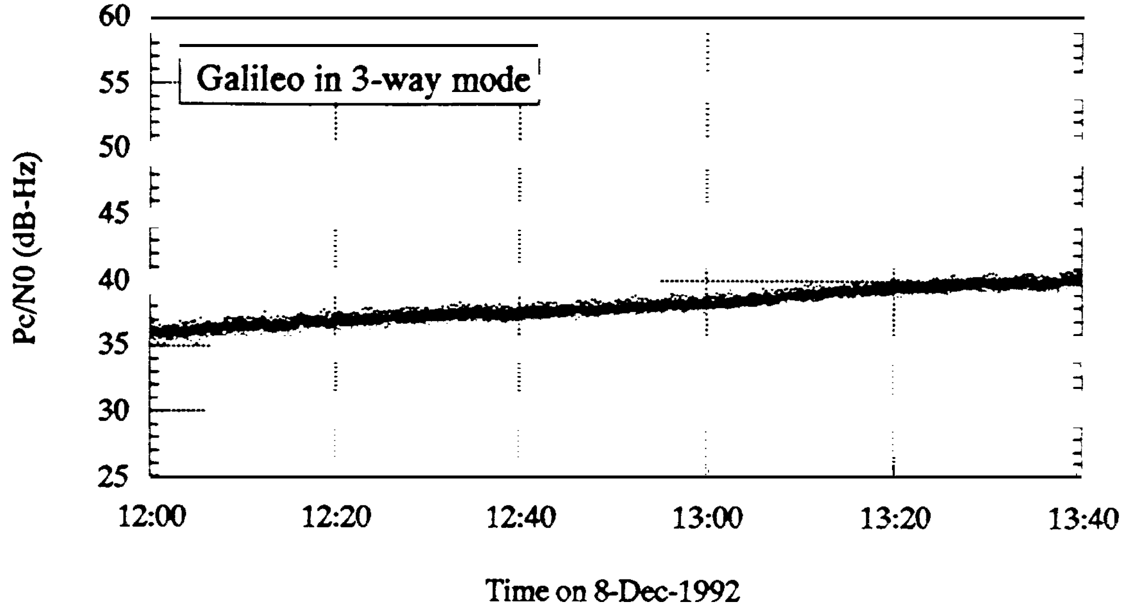
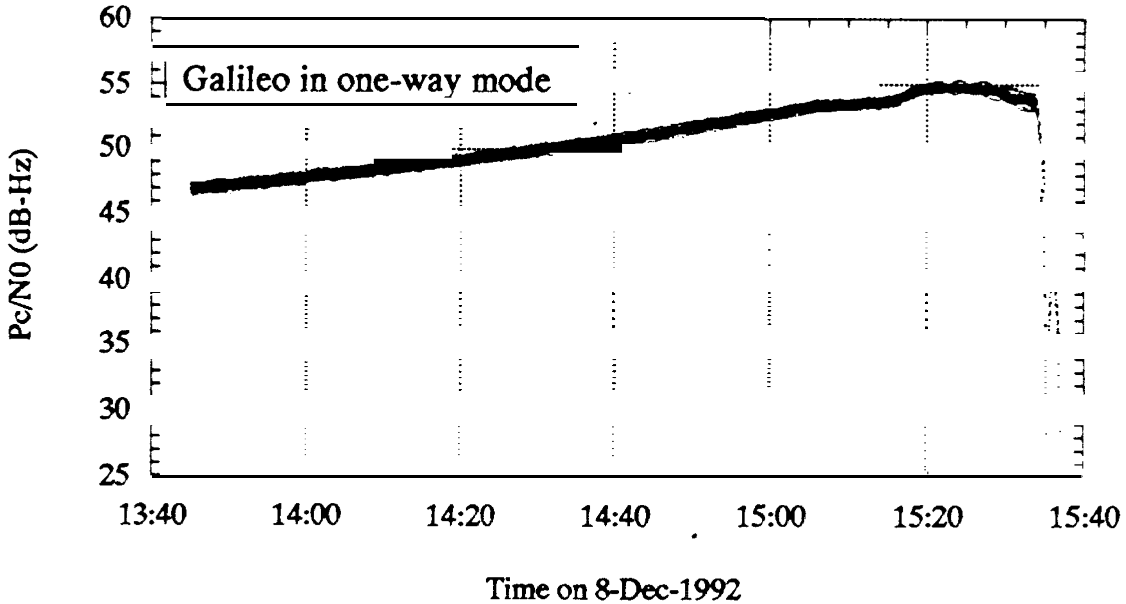
TDRSS FREQUENCY SCHEME
GALILEO FLY-BY CONFIGURATION



SSA1/2 CENTER FREQUENCIES ARE FIXED ON KU-BAND DOWNLINK, TDRSS FREQ SYNTH IS TUNABLE SO THAT S-BAND CENTER FREQUENCY CAN BE SET FROM 2,2-2,3 GHZ IN .5-MHZ STEPS, WE SET BOTH CHANNELS TO 2295.5-MHZ CF.

Power of Galileo S-band carrier received t White Sands





Effective S-band frequency received at White Sands